International UTC and TAI comparison based on BDS PPP

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Abstract The BeiDou navigation satellite system (BDS) developed by China, and provided official service for Asia-pacific region freely since 2012. With development of BDS, BDS-based time transfer has become an important research direction in BDS's application fields. At present, the main method of BDS-based time transfer is BDS Common View (BDS CV), which can reach nanoseconds magnitude, which, according to previous studies by other researchers. In this contribution, we further investigate the performance time transfer based on BDS precise point positioning (PPP) toward UTC/TAI compute. Our investigation based on BDS PPP by using developed quad-constellation GNSS software, which called National Time System Center's (NTSC) Bernese. Moreover, a long-term data analysis is presented. Our numerical tests, carried out using more than 730 day's data of above 14 stations form January 1, 2015 to January 1, 2017, suggest three major findings. First, Compared with BIPM TAI PPP solutions, the uncertainty of NTSC's Bernese GPS PPP can reach about 0.1 ns by using IGR products and about 0.2 ns by using multi-GNSS precise products, such as GBM, COM. For BDS PPP solutions. Second, the solutions of GPS PPP are regarded as reference values. It is demonstrated that the uncertainty of time transfer based on BDS PPP can reach better 1 ns toward UTC/TAI comparison for the statistics of 30 days-arc solutions, while 0.1 ns magnitude can be achieved for the statistics of daily solutions due to the influence of the day boundary discontinuity. Third, four different processing strategies of BDS PPP which include tropospheric delay fixed, tropospheric delay and coordinates fixed, coordinates fixed, and BDS-only are tested. Results show that the comparable uncertainty can be achieved for four processing strategies. Hence, one can conclude that the time transfer based on BDS-only PPP show a good performance toward UTC/TAI computation.

Keyword: Precise point positioning; BDS; UTC/TAI comparison; Bernese

1 Introduction

It has long been know that the method of GPS Common-View (CV) time and frequency was proposed since 1980s, Allan used the pseudorange observations and explicit differencing of the GPS data collected at the two international timing laboratories (Allan and Weiss 1980). The uncertainty of CV time transfer can reach few nanoseconds. Nowadays, GPS CV has been widely used for time and frequency by international time laboratories, due to its low cost and attractive accuracy.

However, the Common View method is known to be affected by the distance between station pair or time-link (Lee et al. 2008). Thanks to International GNSS Service (IGS), which has provided precise orbits and clock products (Griffiths and Ray 2009), another technique called All in View (AV) were proposed by Petit and Jiang (2008a). The method is not like CV, it is not subject to the distance between different international time laboratories. The comparable accuracy as GPS CV can achieve. Unfortunately, the uncertainty of GPS CV and GPS AV are limited by pseudorange observations. Hence, GPS precise point positioning (PPP) (Kouba and Héroux 2001), which uses combination of pseudorange and phase observations are applied (Dach et al. 2003; Zhang et al. 2010). The uncertainty of GPS PPP can reach sub-nanosecond magnitude as well as greater frequency stability in the short term. At the BIPM, the technique has been operationally used to compute time links for International Atomic Time TAI since September 2009 and now concerns over 50% of the more than 70 laboratories contributing to TAI and UTC (Petit 2009; Petit and Jiang 2008b).

China is in the process of developing the BeiDou navigation satellite system (BDS), which adopts its own time (BeiDou Time, BDT) and coordinate system (China Geodetic Coordinate System 2000, CGCS2000) (CSNO 2013). When fully deployed, the BDS constellation will consist of a worldwide coverage based on 35 satellites which include 5 Geostationary Earth Orbit (GEO) satellites, 27 Medium Earth Orbit (MEO) satellites and 3 Inclined Geosynchronous Satellite Orbit (IGSO) satellites. Currently, the constellation comprises a total of 15 satellites, with 5 of each group. The GEO and IGSO satellites can be observed from the Asia-Pacific region, and from part of Europe. With development of BDS, BDS-based time transfer has become an important research direction in BDS's application fields. At present, the main method of BDS-based time transfer is BDS Common View (BDS CV), which can reach nanoseconds magnitude (Guo et al. 2015b; Huang and Defraigne 2016; Kong et al. 2014; Yuan and Guang 2012). In addition, many scholars have done research on time transfer based on BDS PPP (Guang et al. 2014; Zhang et al. 2015). However, the above research only focused on the method of time transfer, and did not apply BDS PPP to Universal Time Coordinated (UTC) and International Atomic Time (TAI) comparison, moreover, there is no long-term data analysis for BDS PPP time transfer. In this contribution, based on Bernese 5.2 (Dach et al. 2015), which had been developed for quad-constellation GNSS data processing and called National Time System Center's (NTSC) Bernese. We then investigate the UTC/TAI comparison based on BDS PPP, moreover, a long-term data analysis is indicated. We expect a good performance for BDS PPP time transfer toward UTC/TAI comparison.

In this work, observation data from 14 stations which come from international time laboratories or globally-distributed stations from IGS Multi-GNSS Experiment (MGEX) (Montenbruck et al. 2017) network is selected. The datasets are processed by using BDS PPP technique, from DOY 1, 2015 to DOY 1, 2017, to investigate the reliability of BDS PPP on International UTC/TAI comparison. The remaining paper is organized as below. In Section 2 describes the ionosphere-free (IF) observation model of PPP. After a brief statement about the data and processing strategy in Section 3. In Section 4, at first, we verify the feasibility of NTSC's Bernese 5.2 software toward UTC/TAI comparison by comparing the results of GPS PPP provided by Bureau International des Poids et Mesures (BIPM). Second, the reliability of the precise products, such as GBM, COM (ftp://cddis.gsfc.nasa.gov/pub/gps/pro ducts/mgex/), which provided by MGEX are verified. Finally, comparing with GPS PPP, the results of BDS PPP are analyzed. In Section 5, the conclusions are drawn.

2 Ionosphere-Free PPP observation Model

The undifferenced ionosphere-free observations for pseudorange P and carrier phase Φ can be written as follows:

$$P_{r,IF}^{s} = \rho_{r}^{s} + dT_{r} - dt^{s} + Trp_{r}^{s} + \varepsilon_{P,IF}^{s} \tag{1}$$

$$\Phi_{r,IF}^{s} = \rho_{r}^{s} + dT_{r} - dt^{s} + Trp_{r}^{s} + \lambda_{IF} N_{r,IF}^{s} + \varepsilon_{\Phi,IF}^{s} \tag{2}$$

where indices *s* and *r* refer to the satellites and receiver, respectively. ρ denotes the geometric distance between the satellite and receiver. dT_r and dt^s refer to the clock error of the receiver and satellites, respectively. Trp is the slant tropospheric delay. $N_{r,IF}^{s}$ is the float ambiguity. λ_{IF} is the wavelength. $\varepsilon_{P,IF}^{s}$ and $\varepsilon_{\Phi,IF}^{s}$ include the measurement noise and multipath error for the ionosphere-free pseudorange and carrier phase observations.

Traditional PPP is usually used in geodetic survey (Cai et al. 2015; Ge et al. 2007; Li et al. 2015b). For time and frequency transfer, receivers in different station are connected to their time and frequency references generating, such as the 1 PPS signal and 5/10 MHz frequency signal (Guang et al. 2014). **Figure 1** shows the PPP time transfer principle. Based on the atomic clock, receivers acquire phase and code observations from all satellites in view. Each station calculates its clock difference between UTC(i) and the IGST. As show in **Figure 1**, station A and station B time different UTC(i)- UTC(j) can be calculated. And the equal can be expressed as follow:

UTC (i)- UTC (j)= (UTC (i)-IGST) -(UTC(j)-IGST) (3)

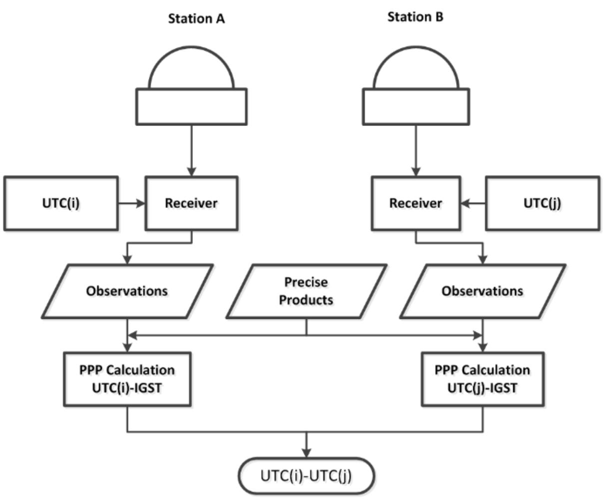


Figure 1 PPP time transfer principle diagram

It should be noticed that the clock errors calculated by PPP including the hardware delay etc. should be corrected. Because the correction method is more complex, the correction process will not be presented herein.

3 Experimental Data and Processing Strategy

3.1 Dataset

BIPM provides the 30 days arc solutions of GPS PPP using IGR products provided by IGS about the station in International timing laboratories every month (ftp://ftp2.bipm.org/pub/tai/). Hence, in order to investigate the feasibility of NTSC's Bernese 5.2 software toward International UTC/TAI comparison, the results provided by BIPM are used as an external reference values. **Figure 2** displays the geographical distribution of 14 stations which includes 7 stations in International time laboratories and 7 MGEX stations used in this work. It should note that 7 stations in International time laboratories are used to verify the feasibility of NTSC's Bernese 5.2 software and the reliability of GBM or COM products. Currently, there are few stations that can observe BDS satellites in International timing laboratories, such as BRUX, ROAP. Hence, the feasibility of BDS PPP toward International UTC/TAI comparison are experimented by using other 7 MGEX stations and part of station in International timing laboratories. The selected MGEX stations all connected to the high-performance atomic clock. The summary of above stations information is listed in **Table 1**. More than 730 day's data of above the station form January 1, 2015 to January 1, 2017 are then analyzed.

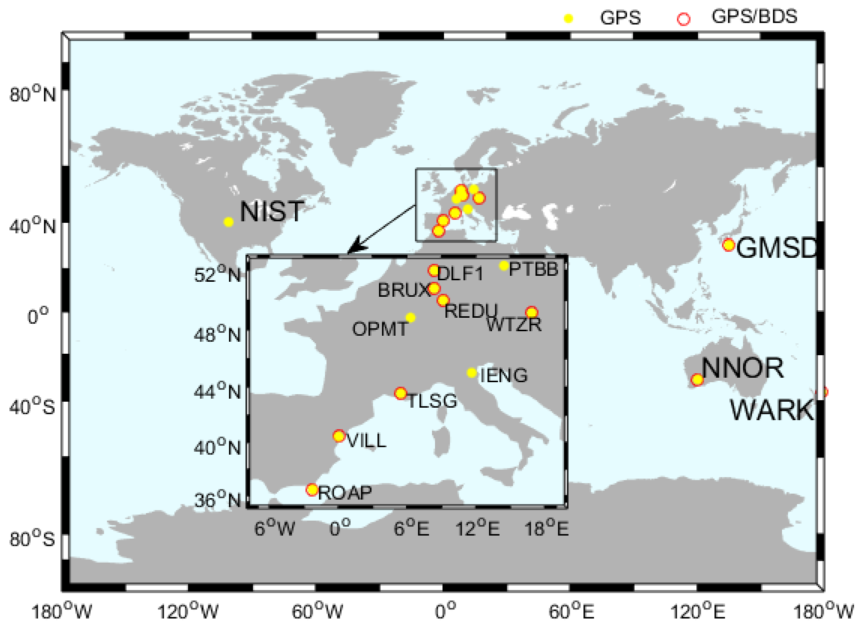


Figure 2. The distribution of multi-GNSS stations from IGS and MGEX networks.

Table 1. The summaries of stations information

Station	Receiver	Antenna	Clock
REDU	SEPT POLARX4	SEPCHOKE_MC	External Cesium
DLF1	TRIMBLE NETR9	LEIAR25.R3	External Cesium
GMSD	TRIMBLE NETR9	TRM59800.00	EXTERNAL Cesium
VILL	SEPT POLARX4	SEPCHOKE_MC	EXTERNAL Cesium
BRUX	SEPT POLARX4TR	JAVRINGANT_DM	EXTERNAL Cesium
WTZR	LEICA GR25	LEIAR25.R3	EXTERNAL H-MASER
ROAP	SEPT POLARX4TR	LEIAR25.R4	EXTERNAL H-MASER

WARK	TRIMBLE NETR9	TRM55971.00	EXTERNAL H-MASER
NIST	NOV OEM4-G2	NOV702	EXTERNAL H-MASER
PTBB	ASHTECH Z-XII3T	ASH700936E	EXTERNAL ACTIVE H-MASER
IENG	ASHTECH Z-XII3T	ASH701945C_M	EXTERNAL H-MASER
TLSG	SEPT POLARX4TR	TRM59800.00	EXTERNAL DORIS
NNOR	SEPT POLARX4	SEPCHOKE_MC	EXTERNAL SLAVED CRYSTAL
OPMT	3S-02-TSADM	3S-02-TSADM	EXTERNAL UTC(OP)

3.2. Processing Strategy

Table 2 summarizes the detailed processing strategy for GPS PPP or BDS PPP. IGR and COM precise orbit and clock products at intervals of 15min and 5min, respectively, are employed. The interval of GBM products are 5min and 30s respectively.Note that the differential code bias (DCB) are corrected by the DCB products (P1C1) provide The Center for Orbit Determination in Europe (COD) for GPS PPP, while the DCB does not need to be corrected for BDS PPP based on ionosphere-free linear combination (LC) observation because ionosphere-free LC pseudorange is used for satellite clock estimation (Ge et al. 2017; Guo et al. 2015a).

Table 2. Summary of PPP processing strategies

Items	Descriptions
Number of stations	14
Number of satellites	GPS:32; BDS :14
Estimator	Least squares (LSQ) estimator
Observables	Undifferenced ionosphere-free combined observables for code and phase observations
Signal selection	GPS: L1/L2; BDS: B1/B2;
Sampling rate	300s
Elevation cutoff	3°
Observation weighting	A priori precision 0.6m and 0.001m for raw code and phase observations, respectively Elevation-dependent, 1 for e>30°, otherwise $\cos(e)^2$
Phase wind-up	Corrected (Wu et al. 1992)
Tropospheric delay	ZHD: corrected with GMF model (Boehm et al. 2007) ZWD: estimated as a continuous piece-wise linear function (2 h parameter spacing), GMF (Boehm et al. 2007) mapping function
Tidal displacements	Solid Earth tide, pole tide, ocean tide loading corrections refer to IERS

	Conventions 2010 (Petit and Luzum 2010)
Relative effect	Corrected
Sagnac effect	Corrected
Satellites antenna PCOs and PCVs	PCO and PCV correction for GPS are from igs08.atx
Receiver clock	Estimated as white noise
Station coordinates	Estimated as static
Phase ambiguities	Estimated; float value

In this contribution, the main experiments are displayed in **Table 3** .

For solutions1, solutions2 and solutions3, GPS PPP are experimented by using different precise products. The BIPM TAI PPP solutions are regarded as external values. The purpose is to verify the reliability of time transfer by using the software and Multi-GNSS precise products on the International UTC/TAI comparison.

For the performance of BDS PPP time transfer toward UTC/TAI comparison. The solutions4 and solutions8 are to prove the performance of BDS PPP on the International UTC/TAI comparison and to investigate the effect of BDS PPP by using different products. In general, the parameter of PPP include coordinate, receiver clock error, tropospheric delay and float ambiguity. In order to investigate the impact of other parameters on the solution of clock error, the experiment of solutions4, solutions5, solutions6 and solutions7 are done.

The daily coordinates of these station are estimated using IGS final orbit and clock products in static mode or IGS weekly SINEX (Solution Independent Exchange format) solutions. The daily solution is then applied to all test in this contribution. Note that the solution of GPS PPP will be regard as external reference values for proving the feasibility of BDS PPP on International UTC/TAI comparison in solutions4-8 due to no other more reliable results as external reference at present.

Table 3. The summaries of experiments.

	IGR products	GBM products	COM products	Coordinates fixed	ZTD fixed
Solutions1-GPS PPP	√				
Solutions2-GPS PPP		√			
Solutions3-GPS PPP			√		
Solutions4-BDS PPP		√			
Solutions5-BDS PPP		√		√	
Solutions6-BDS PPP		√			√
Solutions7-BDS PPP		√		√	√
Solutions8-BDS PPP			√		

4. Results and Analysis

4.1 The reliability of the software and multi-GNSS products

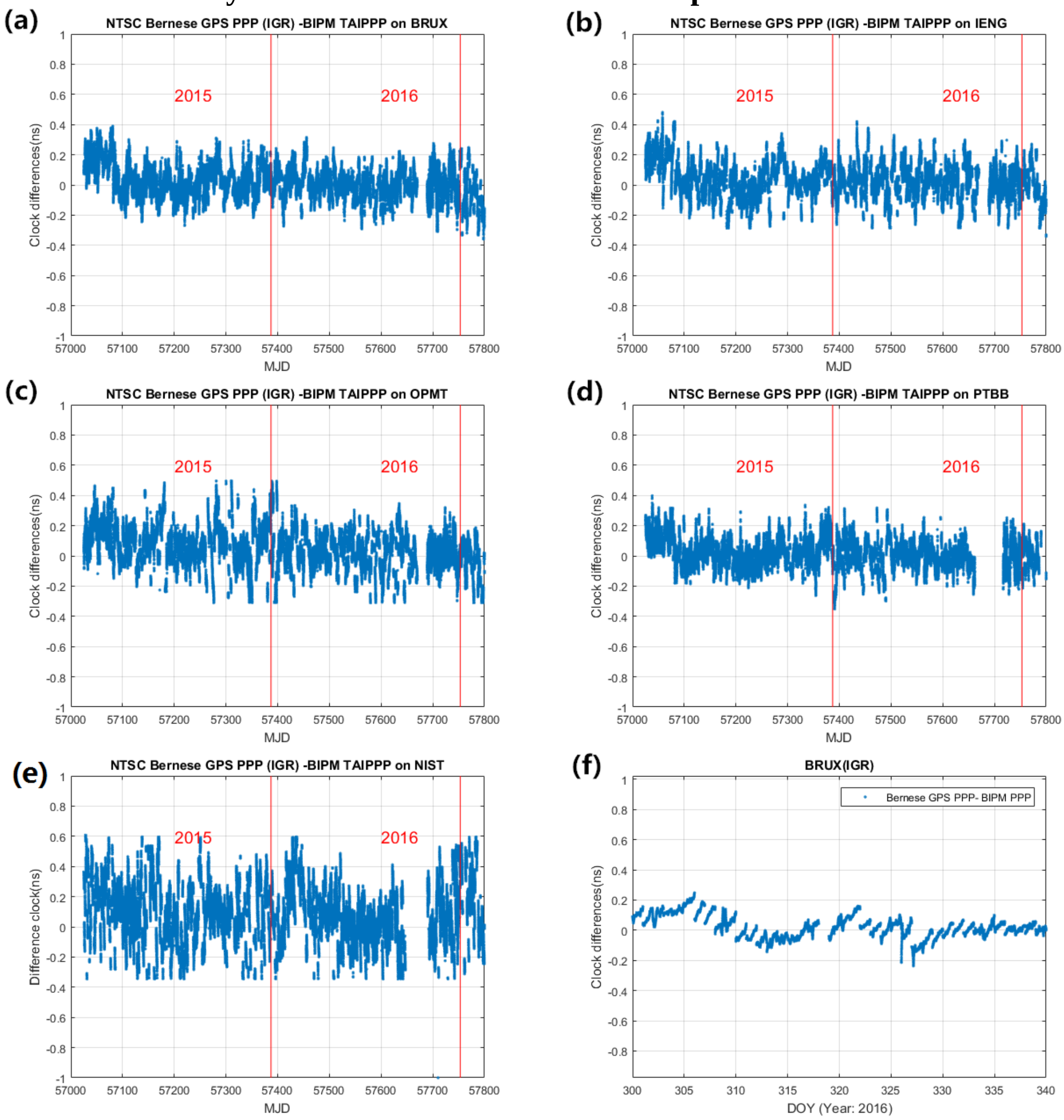


Figure 3 Differences between BIPM PPP and NTSC's Bernese GPS PPP solutions on 6 stations using IGR products.

The clock differences between BIPM TAIPPP and more than 2 years Bernese GPS PPP solutions for single station using IGR products are illustrated in **Figure 3**. Note that the daily arc solutions are obtained from Bernese software in this contribution. The solutions of other sites show the similar feature at different times and thus not be present herein. The figure confirms that the differences are basically stable between -0.2 and 0.2 ns. But the solutions are poor at NIST station **Figure 3 (e)**, the main reason may be that the quality of the observations is poor. On the other handle, we can see that there is obvious day boundary discontinuity at **Figure 3 (f)**. That may be caused by pseudorange noise (Defraigne and Bruyninx 2007). The day boundary discontinuity will not be mitigated by using 30s clock products. At present, there are many scholars who have done research on how to mitigate it (Dach et al. 2006). We will not elaborate on it herein.

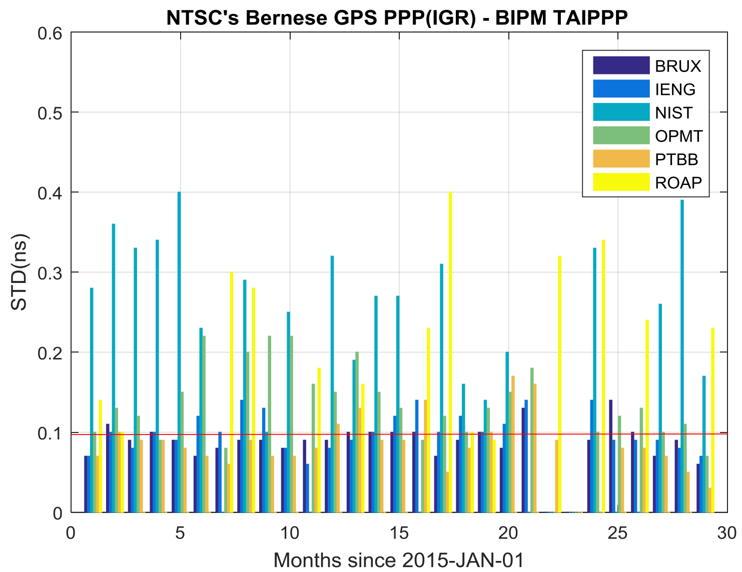
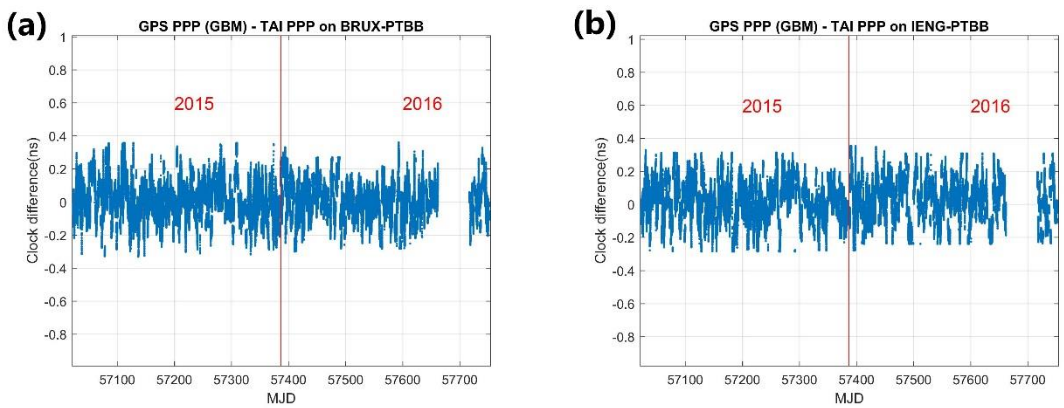


Figure 3 The statistics analysis of 30-days arc solutions on six sites, computed with the BIPM PPP, and Bernese GPS PPP solutions with IGR products.

In order to evaluate uncertainty of PPP solution, the authors introduce standard deviations (STD) as its evaluation criteria. The BIPM PPP solutions are regarded as the external reference values in this section. We use month solutions as a data arc for data statistics. Hence, **Figure 3** illustrates the statistics of solutions for 6 sites on International time laboratories, which computed with the BIPM PPP solutions and NTSC's Bernese GPS PPP solutions, over the 28 months period from January 1, 2015 to May 1, 2017. The figure confirms the announced uncertainty of NTSC's Bernese GPS PPP-based UTC/TAI comparison: STD of the clock differences reach about 0.1 ns. As show in **Figure 3**, the part of the statistics is poor, that's mainly the problem of the NIST and ROAP sites. Compared with the solutions of BIPM TAIPPP, the solutions of NTSC's Bernese show a good performance form the overall solutions. It also illustrates the reliability of the software form another perspective.



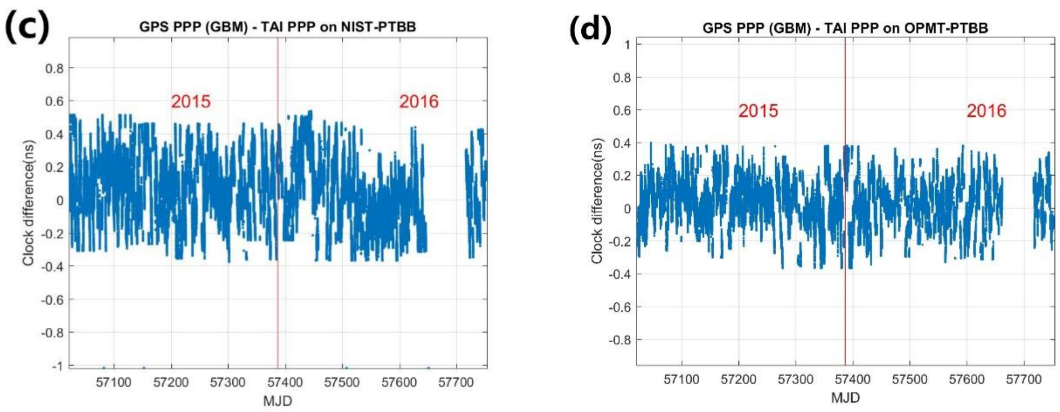


Figure 4.. Differences between BIPM PPP and NTSC's Bernese GPS PPP solutions on four time-links using GBM products

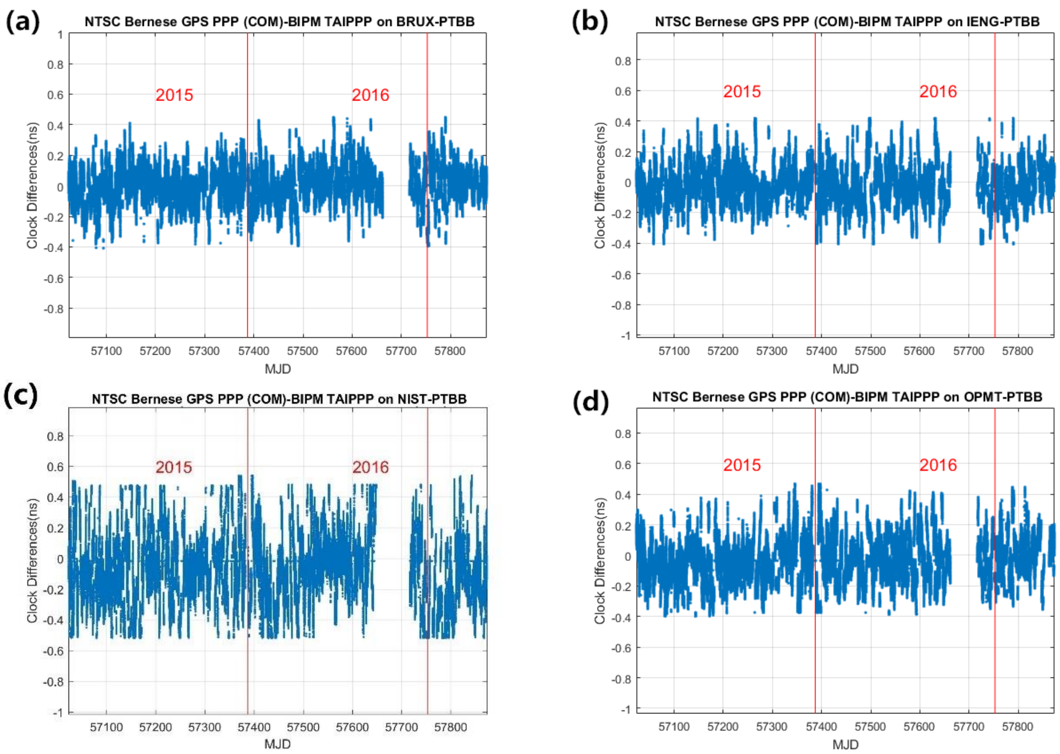


Figure 5.. Differences between BIPM PPP and NTSC's Bernese GPS PPP solutions on four time-links using COM products

As shown in **Figure 4** and **Figure 5**, the clock differences between BIPM TAI PPP and NTSC's Bernese GPS PPP solutions on four time-links by using GBM or COM products are presented. **Figure 4** and **Figure 5** indicated that the solutions are relatively stable and can achieve better uncertainty. **Figure 5** depicts the solutions using COM products, and the stable results are presented in (a), (b) and (d). Note that the poor performances are shown in **Figure 4 (c)** and **Figure 5 (c)**. The reason is the same as stated before. It should be mentioning that there are several gaps in **Figure 4** and **Figure 5**. The main reason is that the receiver about TAI PPP provided by BIPM at PTBB station and the receiver about PTBB provided by IGS are inconsistent in that two months.

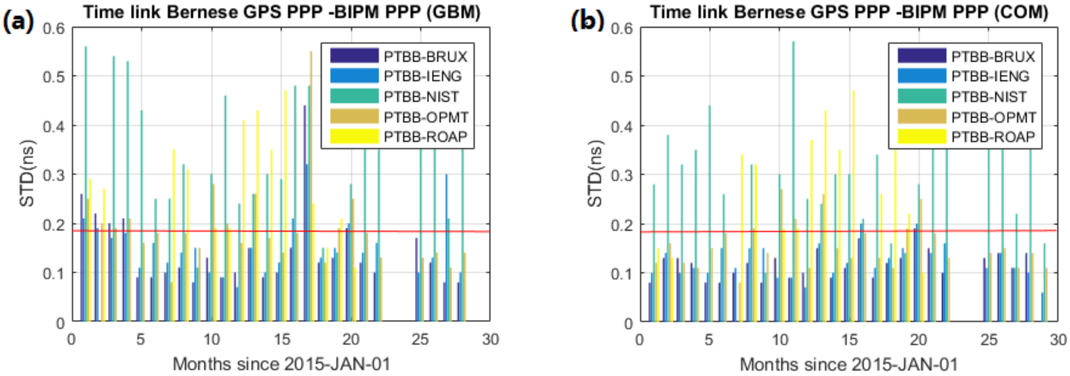


Figure 6. The statistics analysis of 30-days arc solutions on five time-links, computed with the BIPM PPP, and Bernese GPS PPP solutions with GBM or COM products.

The statistics of 30-days arc solutions are displayed in **Figure 6** by using GBM or COM products on five time-links. As shown in **Figure 6**, the uncertainty of the solutions can achieve better than 0.2 ns for different multi-GNSS products expect for PTBB-NIST and PTBB-ROAP. The different uncertainty can be obtained from different time-links. The mainly reason may be different observations conditions, receiver, antenna, and external clock et al.

4.2 The performance of the BDS PPP

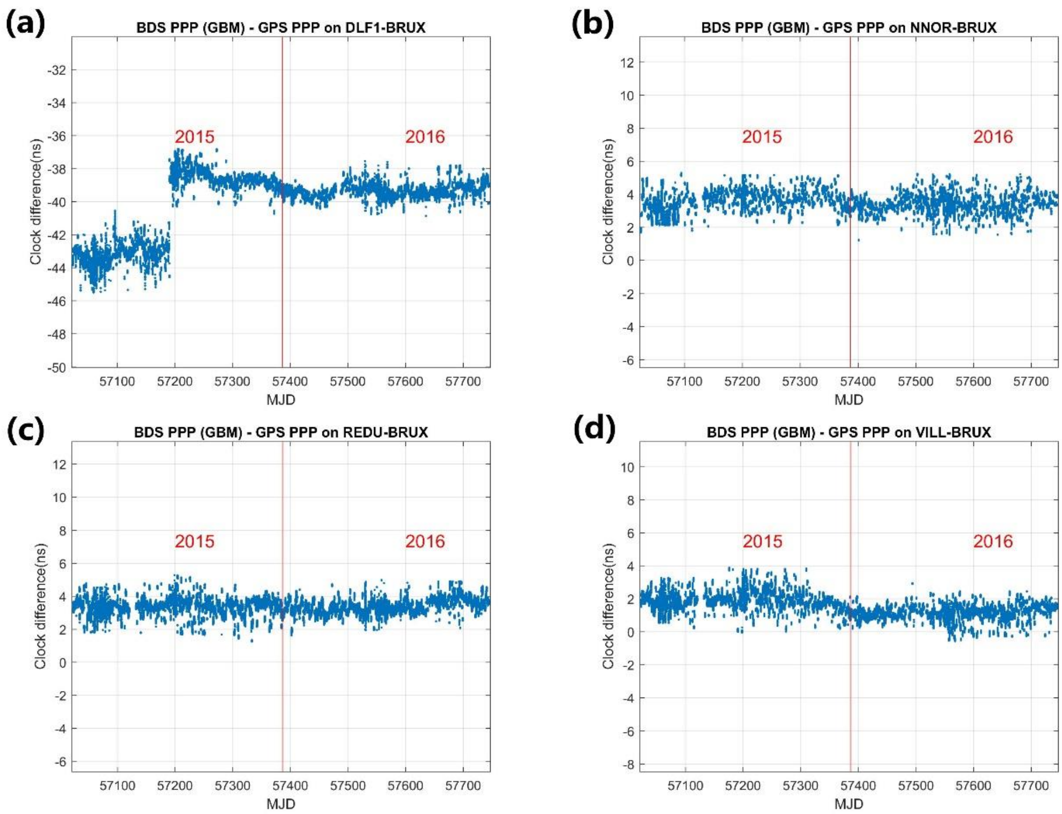


Figure 7. BDS PPP (GBM)-GPS PPP on four time-links by using GBM 30s products.

The clock differences of BDS PPP and GPS PPP by using GBM products are displayed on **Figure 7**. It should be mentioned that the BDS PPP solutions in **Figure 7** with troposphere delay and coordinates fixed. There is an offset at **Figure 7** (a), that's caused by the adjustment of the local clock. In addition to the above two points,

compared with GPS PPP solutions, the solutions of BDS PPP can achieve a good performance. However, there is a system bias between the solutions of BDS PPP and GPS PPP solutions, that's because that the difference frequencies and signal structure of the individual GNSS, the code bias values are different in single multi-GNSS receiver. The differences between them are usually called inter-system biases (ISB) for code observations (Li et al. 2015a). On the other hand, the main factors of the uncertainty of BDS PPP solutions includes the receiver, antenna, the observations environment, external clock, the structure of the satellite geometry, and processing strategies. Compare **Figure 7** (a) and **Figure 7** (b), the uncertainty on DLF1-BRUX show a better performance. The root mean squares (RMS) of multipath are 0.43 m and 0.34 m at DLF1 and GMSD station on DOY 3, 2016, respectively. The type of receiver and external clock are the same at DLF1 and GMSD from **Table 2**. The sky plot of BDS constellations on DLF1 and GMSD stations are presented in **Figure 8**. In addition, the average of Geometric Dilution of Precise (GDOP) are 10.9 and 2.9 on DLF1 and GMSD, respectively. Hence, the reason of poor performance of GMSD-BRUX may be due to the poor performance of the external clock on GMSD. Compared with **Figure 7** (a), the uncertainty of solutions of **Figure 7** (d) is poor. That's mainly due to its poor observations conditions. Although, the uncertainty of different time-links is difference, but BDS PPP solutions are still relatively stable on UTC/TAI comparison in current state of the BeiDou system.

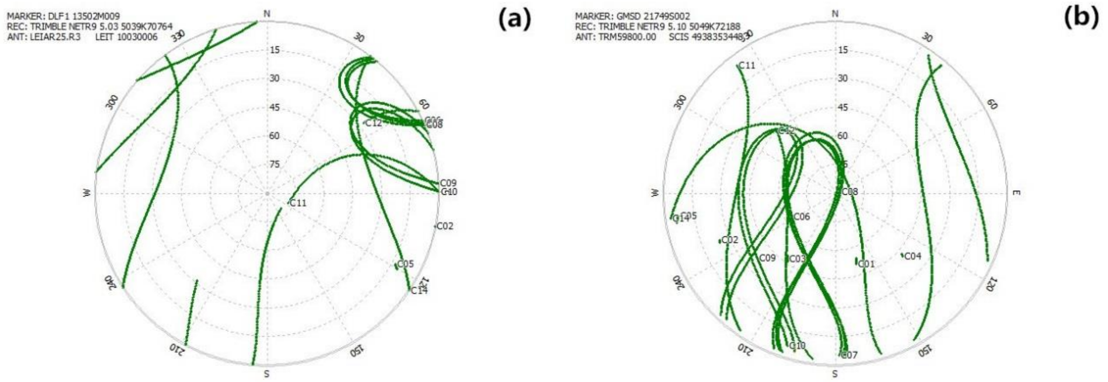


Figure 8. Sky plot of BDS constellations on DLF1 and GMSD.

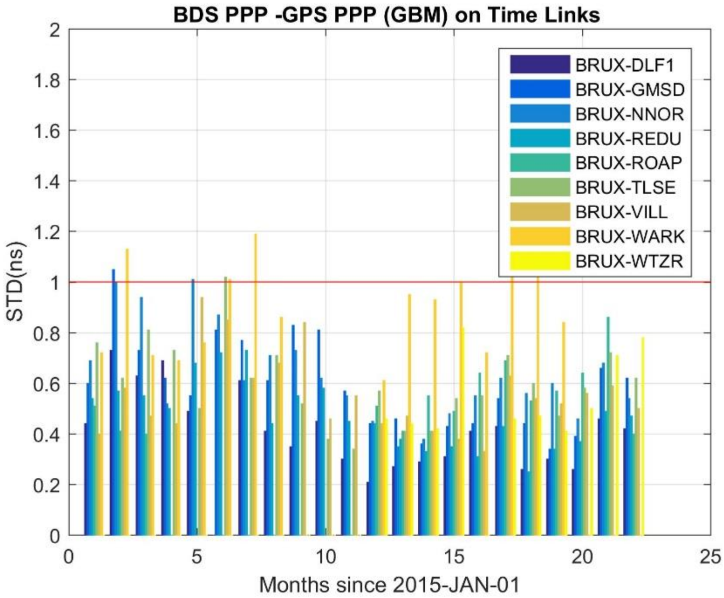


Figure 9. The statistics analysis of 30-days arc solutions on nine time-links, computed with the BDS PPP, and GPS PPP solutions with GBM 30s products.

In order to investigate the uncertainty of BDS PPP time transfer, the GPS PPP solutions are regarded as external reference values. The 30-days arc solutions are analyzed on all time-links according to the strategies of BIPM. The all statistics are illustrated in **Figure 9**. As shown in **Figure 9**, the uncertainty of BDS PPP solutions can be better than 1 ns for all time-links. Among them, some of the results are poor, for example, the poor performance of WTZR-BRUX are caused by observations conditions and the characteristic of the atomic clock. Overall, the BDS PPP time transfer show a good performance toward UTC/TAI comparison.

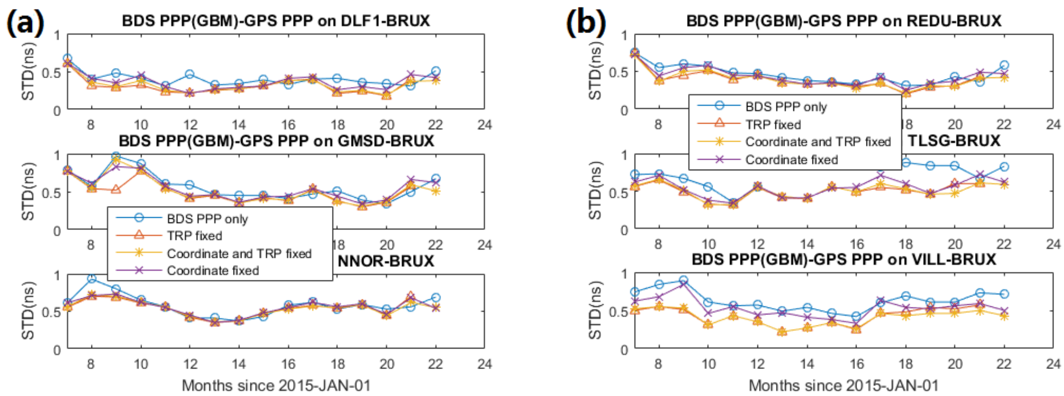


Figure 10. The STD of four processing strategies on time-links.

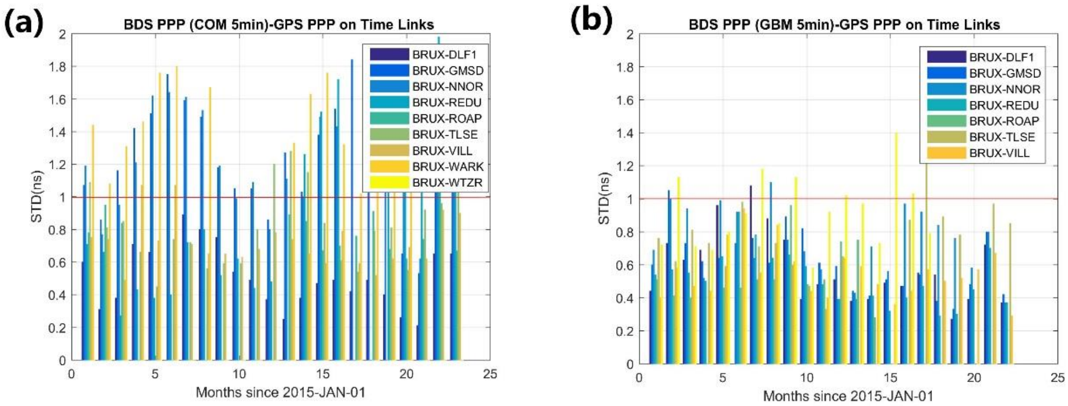


Figure 11. The comparison of COM and GBM products.

The uncertainty of time transfer based on BDS PPP not only affected by observations conditions, receiver, antenna, and external clock et al. but also by processing strategies and precise products. Therefore, the four processing strategies are investigated and listed in **Table 3**. The STD are illustrated in **Figure 10**. Compared with BDS PPP-only, the other three processing strategies show a good performance. The best uncertainty of BDS PPP can be achieved with tropospheric delay fixed or tropospheric delay and coordinates fixed. However, the differences of four processing strategies are very small. Their differences are only about 0.1 ns. One can conclude that the uncertainty can achieve better 1 ns based on BDS PPP without external auxiliary conditions. On the other hand, the uncertainty of precise products is also one of the main factors in BDS PPP time transfer. Hence, the comparison of COM and GBM products are illustrated in **Figure 11**. The interval sample of COM and GBM clock products are used in this section. Compared with GBM products, the uncertainty of BDS PPP show a relatively poor performance. That's because that the COM products have no GEO satellites information as well as the characteristics of the products itself.

Currently, the day boundary discontinuity is still an unsolved problem. The statistics of 30-days arc solutions include the error of the day boundary discontinuity. Hence, the statistics of daily solutions are investigated. As shown in **Figure 12**, the statistics of daily solutions on time-links are presented, and the solutions of other time-links show the same feature, hence, we do not describe it in detail. Overall, the uncertainty can reach better 0.1 ns, although some of the results are poor. The main reasons are the observations and the accuracy of products.

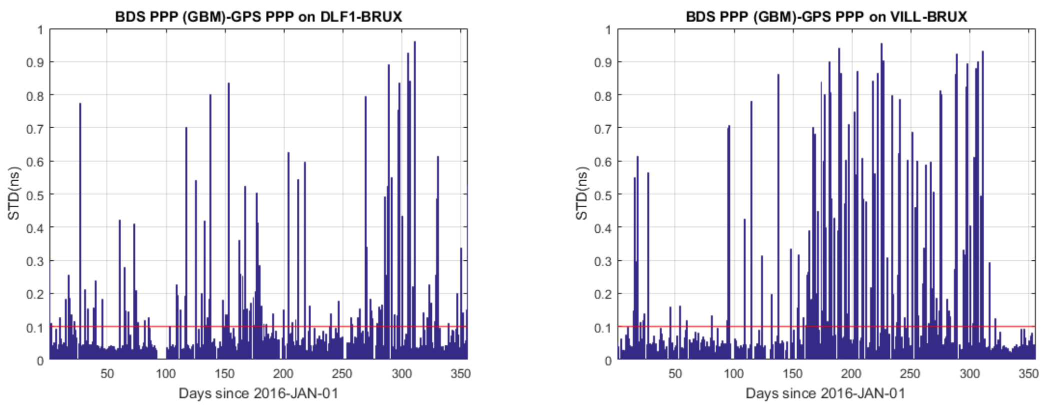


Figure 12. The statistics of daily solutions on two time-links.

5 Conclusion

In this contribution, we focus on the performance of time transfer based on BDS PPP toward TAI/UTC computation. 14 stations which includes 7 stations in International time laboratories and 7 MGEX stations are used in this study. And we analyzed more than 880 day's data of above the station form January 1,2015 to May 1, 2017. Firstly, the reliability of the software and multi-GNSS products are analyzed. In this section, the solutions of BIPM TAIPPP are regarded as external reference values. Then, the performance of BDS PPP and four processing strategies comparison are presented. And the GPS PPP solutions are regarded as external reference values in this section.

Compared with BIPM TAIPPP solutions, the uncertainty of NTSC's Bernese software solutions can achieve better 0.1 ns by using the same products and observations data. The reliability of the software is obtained. On the other hand, the solutions of BIPM TAIPPP which use IGR products are regarded as external reference values for verifying the reliability of multi-GNSS precise products, the different precise clock products have a different reference clock. Hence, the time-link solutions are presented.

Comparative analysis that the uncertainty can reach about 0.2 ns by using multi-GNSS products. One can conclude that the multi-GNSS products can be used for PPP time transfer and can reach a good performance.

In order to investigate the performance of BDS PPP on UTC/TAI comparison, the GPS PPP solutions are regard as reference values. Comparative analysis that the uncertainty of BDS PPP can reach better 1 ns by using GBM products. The uncertainty will be affected by many factors, such as the receiver, Antenna, the observations environment, external clock, the structure of the satellite geometry, and processing strategies et al. Hence, four processing strategies which include coordinates fixed, troposphere delay fixed, coordinate and troposphere delay fixed and BDS only. Results show that the comparable uncertainty can be achieved for four processing strategies. Hence, one can conclude that the comparable uncertainty of time transfer can be obtained based on BDS-only PPP toward UTC/TAI computation.

Form the above discussion, for 30 days-arc solutions, the conclusion can be reached that the uncertainty of time transfer based on BDS-only PPP can reach better 1 ns toward UTC/TAI computation, while 0.1 ns magnitude can be achieved for the statistics of daily solutions.

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